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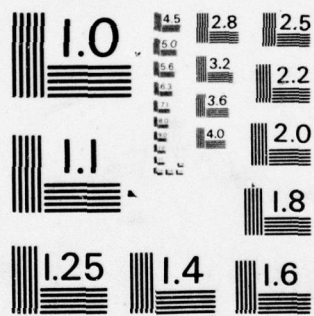
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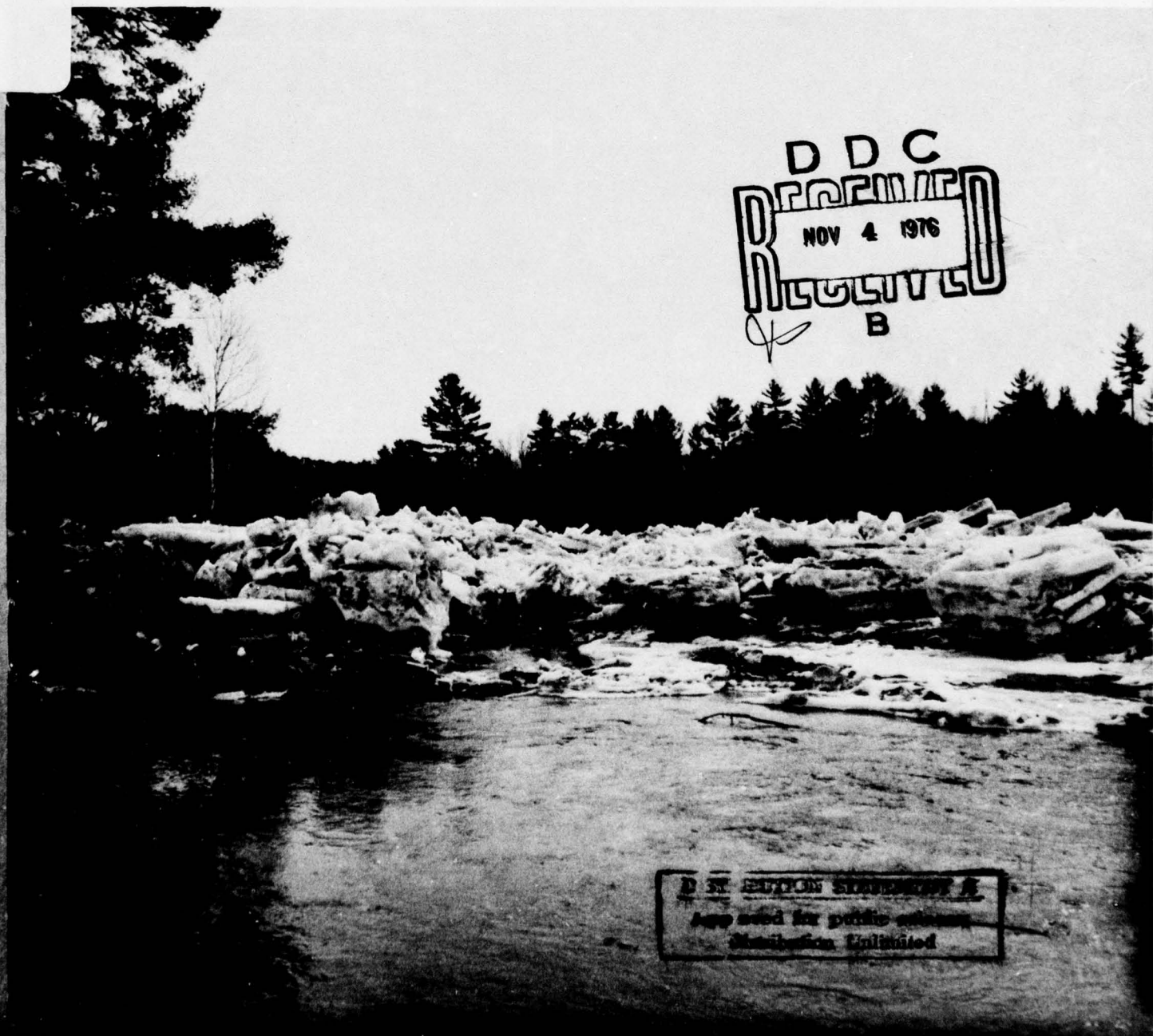
REPORT 76-31



*Analysis of potential ice jam sites
on the Connecticut River at Windsor, Vermont*

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Cover: Typical ice jam in northern New England.

CRREL Report 76-31

Analysis of potential ice jam sites on the Connecticut River at Windsor, Vermont

D.J. Calkins, M.S. Hutton and T.L. Marlar

September 1976

Prepared for

U.S. ARMY ENGINEER DIVISION, NEW ENGLAND, AND
DIRECTORATE OF CIVIL WORKS
OFFICE, CHIEF OF ENGINEERS

By

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CRREL Report 76-31	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ANALYSIS OF POTENTIAL ICE JAM SITES ON THE CONNECTICUT RIVER AT WINDSOR, VERMONT	5. TYPE OF REPORT & PERIOD COVERED	
7. AUTHOR(s) D.J. Calkins, M.S. Hutton and T.L. Marlar	6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS CWIS 31332	
11. CONTROLLING OFFICE NAME AND ADDRESS Directorate of Civil Works Office, Chief of Engineers Washington, D.C.	12. REPORT DATE September 1976	13. NUMBER OF PAGES 39
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) CRREL-76-31	15. SECURITY CLASS. (of this report) Unclassified	
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE		
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES This study was funded in part by the Emergency Operations Center, New England Division, Corps of Engineers, and in part by the Civil Works Ice Engineering Program at CRREL.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Aerial photographs Ice jams Channel morphology Ice jam locations Connecticut River, at Windsor, Vermont Hydraulic analysis		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Sections in the Connecticut River where ice jam potential is high were identified through the use of low-altitude black and white photographs taken during low-flow, ice-free conditions. The hydraulics and mechanics of ice jam initiation were investigated in the river reach where these sections were identified. Certain areas were found in the river that had a high susceptibility to ice clogging, but this high potential decreased with increasing discharge because of the improved surface conveyance of the ice through the reach. The stability of ice floes was established along the channel, but the floes generally became unstable as the flow increased. This was calculated by using a Froude number criterion. Grounding locations for ice became evident when the critical Froude number was zero		

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20. Abstract (cont'd)

for a given thickness and water depth. No single factor was determined to be responsible for initiating the ice jams in the Connecticut River at Windsor. Apparently there existed a multitude of interacting conditions: surface constrictions, possible high backwater conditions from the Brattleboro Dam, a solid ice cover in the backwater of the Brattleboro Dam that prevented ice transport from the Windsor area, deep pools followed by shallow depth sections upstream of bridge piers, a greater ice thickness accumulation of fragmented floes than would result if a uniform cover could be established in the same reach, and the diurnal fluctuation of river stage caused by the release of water at Wilder Dam.

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PREFACE

This report was prepared by D.J. Calkins, Research Hydraulic Engineer, of the Applied Research Branch, Experimental Engineering Division, M.S. Hutton, Geologist, of the Earth Sciences Branch, Research Division, and T.L. Marlar, Supervisory Photographer, of the Engineering Services Branch, Technical Services Division, U.S. Army Cold Regions Research and Engineering Laboratory.

The study was funded in part by the Emergency Operations Center, New England Division, Corps of Engineers, and in part by the Civil Works Ice Engineering Program at USA CRREL, under CWIS 31332.

This report was reviewed technically by Kevin L. Carey and Stephen L. DenHartog of USA CRREL.

The authors wish to express appreciation to Dr. George D. Ashton, Dr. Harlan L. McKim, and Lawrence W. Gatto for their reviews of the report.

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SUMMARY

This report describes a procedure for identifying ice jam locations based on hydraulic conditions in the Connecticut River. The hydraulic analysis consisted of establishing water surface profiles using Computer Program HEC-2, developed by the Hydrologic Engineering Center, Corps of Engineers, Davis, California. Continuity of surface ice discharge was assumed in the river reach studies, and this allowed computation of the ice concentration at various sections to determine the clogging potential of the ice floes.

Once conditions for clogging are identified at critical sections, a Froude number criterion is evaluated to determine ice block stability, and the type of ice jam can be identified. When clogging of ice floes at a particular section is identified, depending on the value of the critical Froude number F_{cr} and the flow Froude number F_0 , a jam forms by juxtaposition of the ice ($F_{cr} > F_0$) or by overturning and stacking of the ice ($F_{cr} < F_0$).

The number of potential ice jam locations for fragmented ice floes decreases as the river flow increases. This identification is quite important, as it implies that there are more potential ice jam sites at low flows because of surface and subsurface constrictions that are quite evident at low water levels. As the water level rises, these obstructions are reduced, allowing greater surface conveyance of ice.

The designs of manmade channels and river modifications are changing to reflect the conditions in which the natural channels are formed. Channels with manmade bends are being designed to accommodate fish habitats as well as to reduce potentially high sediment transport. Reaches with trapezoidal sections to replace oxbow sections are being discouraged and conformity with more existing natural conditions, such as keeping the oxbows but improving the conveyance capacity and stabilizing the banks, is being stressed. For design of such channels in cold regions, an ice jam location check such as the one described in the report would ensure that unfavorable conditions conducive to ice jamming are avoided.

CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

<i>Multiply</i>	<i>By</i>	<i>To obtain</i>
inch	25.4*	millimeter
foot	0.3048*	meter
mile	1.6093	kilometer
foot/second	0.3048*	meter/second
foot ² /second	0.09290304*	meter ² /second
foot ³ /second	0.02831685	meter ³ /second
pound	0.4535924	kilogram
slug/foot ³	515.38	kilogram/meter ³
Btu/pound	2326*	joule/kilogram
Btu/h ft ² °F	5.678263	watt/meter ² kelvin
degrees Fahrenheit	$t_K = (t_F + 459.67)/1.8$	kelvins
degrees Fahrenheit	$t_C = (t_F - 32)/1.8$	degrees celsius

* Exact.

ANALYSIS OF POTENTIAL ICE JAM SITES ON THE CONNECTICUT RIVER, AT WINDSOR, VERMONT

by

D.J. Calkins, M.S. Hutton and T.L. Marlar

INTRODUCTION

The location of ice jams along a river system and the prediction of their occurrences have previously been studied through review of historical records. The systematic analysis of the hydraulic conditions and river ice characteristics that initiate ice jams has been used only rarely. Often the destructive end-products of ice jams have been overstressed, whereas the conditions initiating them have been overlooked, perhaps because of the spectacular results of massive ice piling.

A joint project, therefore, was begun by the New England Division, Corps of Engineers, and the U.S. Army Cold Regions Research and Engineering Laboratory to study the formation and breakup of ice on the Connecticut River between White River Junction and Windsor, Vermont, during the 1974-1975 season (Fig. 1). Past records indicated that frequent ice jams occurred in this reach of the river.

After initial review, it became evident that the river reach selected was too large for complete analysis; therefore, a shorter section, from the railroad bridge in Windsor upstream to Sumner Falls, was chosen for investigation. The total length of this shorter reach was approximately 36,000 ft as measured from U.S. Geological Survey topographic maps. Low-altitude aerial photography was used to delineate stream patterns, rock outcrops and manmade structures, which are often associated with the initiation or formation of ice jams. Aerial photography was also used to document ice conditions in the study reach.

TEST SITE

In August 1974, an aerial photographic mission (altitude 2000 ft, scale 1:3250) was accomplished over the proposed area, and from the photography obtained, a smaller region of the river was selected for detailed analysis (Fig. 1). This consisted of a 6.5-mile stretch of the Connecticut River from Sumner Falls in North Hartland, Vermont, to the southern tip of Chase Island in Windsor, Vermont.

A flood control reservoir exists upriver from the test site on the Ottauquechee River in North Hartland. The outflow from the North Hartland Dam is regulated only during high flows or anticipated extreme rainfall events, so the inflow to the Connecticut River is generally uncontrolled. The Wilder Dam on the Connecticut River in Lebanon, New Hampshire, releases water on a predetermined schedule set by the New England Power Company. This release normally occurs every morning, Monday through Friday, to generate hydroelectric power, and as a consequence, the water level in the test area rises up to 5 ft in late morning to early afternoon depending on the discharge.

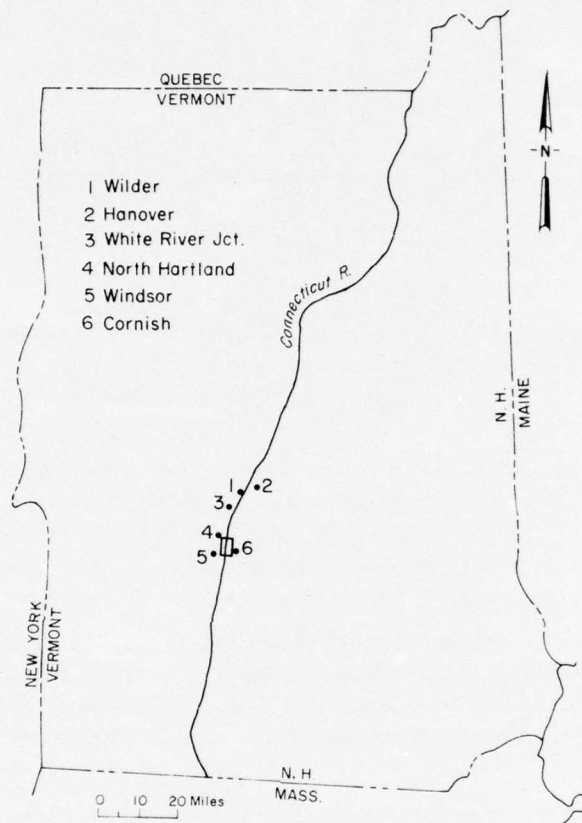


Figure 1. Location of test site.

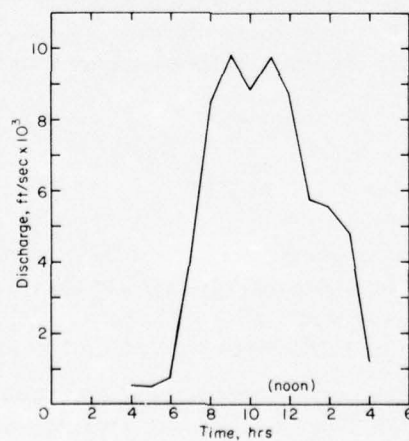


Figure 2. Typical discharge hydrograph for the Connecticut River at White River Junction, 22 October 1974.

A typical discharge hydrograph obtained at White River Junction gaging station is shown in Figure 2 for 22 October 1974. The duration and rise in the hydrograph are generally determined by the anticipated peak power demand and water release schedules set for the entire Connecticut River Basin. Weekend hydropower generation is not usually required at the Wilder Dam or for the other upstream power dams unless unexpected peak electrical demands are reached.

The other significant tributaries of the Connecticut River in the study area are the Mascoma and White Rivers, entering at West Lebanon, New Hampshire, and White River Junction, Vermont, respectively, with the White River Basin being the larger of the two. The river gaging station for the Connecticut River at White River Junction includes the flow from the White River. The Mascoma River is the only river with a potentially significant ungaged winter flow.

The flood control structure at North Hartland and the many upstream mill ponds retain all the ice produced in the Ottauquechee River. The ice supply from the Mascoma River is also limited because of several small control structures between West Lebanon and Lebanon which retain the ice. The significant ice discharge to the study reach is that generated in the White River and in the Connecticut River up to Wilder Dam. The Wilder Dam retains all the ice generated in the Connecticut River and its tributaries up to Barnet, Vermont.

AERIAL PHOTOGRAPHY

Photography obtained for the study of ice jams in the Connecticut River consisted of 9-in. by 9-in. vertical photographs from a Zeiss RMK 15/23 mapping camera with a 6-in. lens, 70-mm vertical photographs from a Hasselblad 500EL camera with a 100-mm planar lens, and 70-mm oblique photographs from a Hasselblad 500EL camera with 80-mm and 100-mm lenses. Films used were Kodak Plus-X aerographic (type 2402), Kodak Tri-X professional panchromatic, and Kodak Ektacolor professional film (type S). The 9-in. by 9-in. photographs were used to prepare a photo-mosaic of the test area. The 70-mm photographs were used to document the ice buildup and related ice features throughout the winter.

Stereographic photography was obtained at an altitude of 2000 ft above mean sea level and this resulted in a variable scale of photography because of changes in terrain elevation along the river. A mean-sea-level altitude was chosen because it provided a basis for scale correction and because it was not possible to maintain a constant distance above ground level due to rapid terrain elevation changes. The scale corrections necessary for the river portion of the photographs were minimal because the elevation drop of the water surface between the upstream section and the downstream section was less than 15.0 ft.

To reduce the cost of acquiring aerial photography, a small format camera system was designed by Thomas Marlair and constructed at USA CRREL. This utilized the door of a Cessna T-41 aircraft and various off-the-shelf camera components (Fig. 3). An additional door was purchased and modified so that it could accept the camera system and still remain easily interchangeable with the standard aircraft door. This system is usable on all Cessna T-41/172 model aircraft and can be readily adapted to other high-wing aircraft. A few of the ice jam surveillance flights were flown using this system to obtain vertical photographs and excellent results were achieved.

CHANNEL MORPHOLOGY – INTERPRETATION OF AERIAL PHOTOGRAPHS

An uncontrolled mosaic of the Connecticut River from Sumner Falls to Chase Island was assembled. The scale of the working photographic prints was approximately 1:3250. Stream features such as alluvial fans, rock outcrops, log debris, channel sinuosity, bank characteristics and

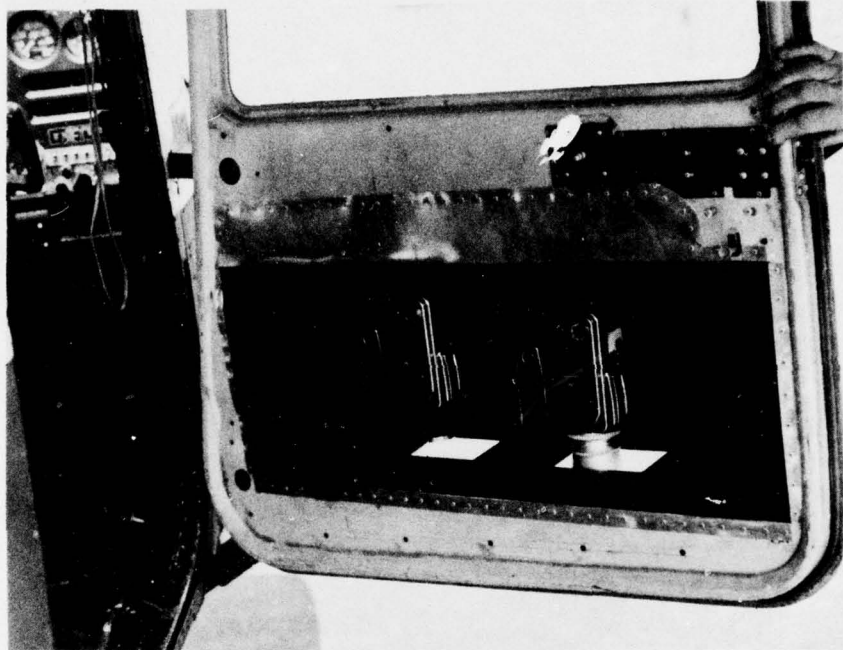


Figure 3. Views of the surveillance cameras mounted in the door of a Cessna T-41 aircraft.

others could be readily identified from low-altitude black and white photographs. The vertical photographs that are presented in this report (Fig. 4) have been reduced from these original 9-in. by 9-in. prints.

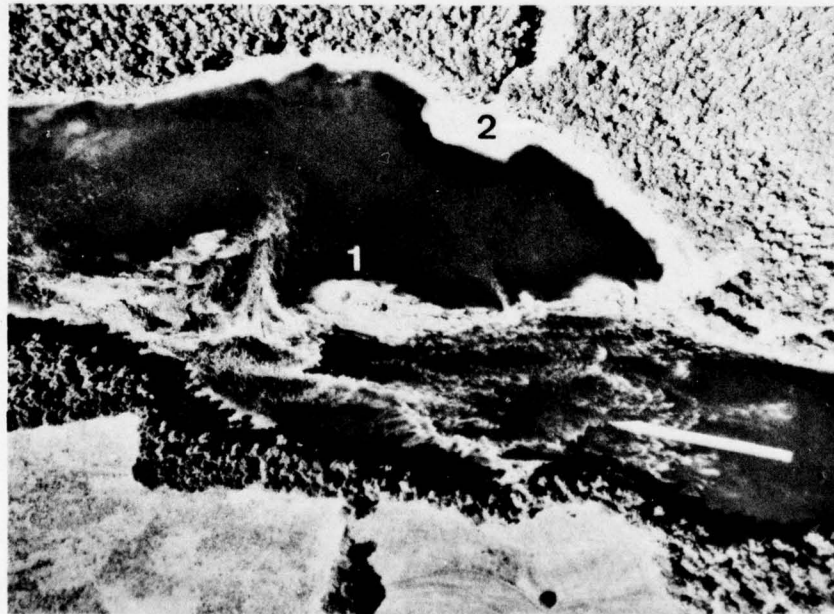
Figures 4a-g show photographs taken with the mapping camera during the month of August at low river flow conditions ($Q \approx 1000 \text{ ft}^3/\text{sec}$). The locations of the cross sections, islands, and tributaries along the test reach are presented in the Appendix.

Areas in a stream channel where ice jams generally form are: 1) constrictions; 2) rock outcrops and manmade structures (bridge piers); 3) long, slow-velocity, deep water pools; and 4) shallow sections across portions of the channel where grounding of ice floes could be initiated. There were three identifiable surface constrictions in the study reach, two occurring as a result of bridge piers and the third at Section 12. Section 12 occurs at a sharp bend ($\sim 70^\circ$) which has riprap on the outside bank to protect the Boston and Maine Railroad bed (Fig. 4d). All visible rock outcrops were identified and they were located between Sections 7 and 8 (Fig. 4e).

The other potential ice jam sites occur between Sections 18 and 19 and Sections 5 and 7, where significant widening of the channel has occurred with deposition zones having been formed into sandbars, visible at low flows (Fig. 4b and c). The material in these areas was classified as a silty sand, while the bed material found in the main sections of the river was classified as a poorly graded gravel.

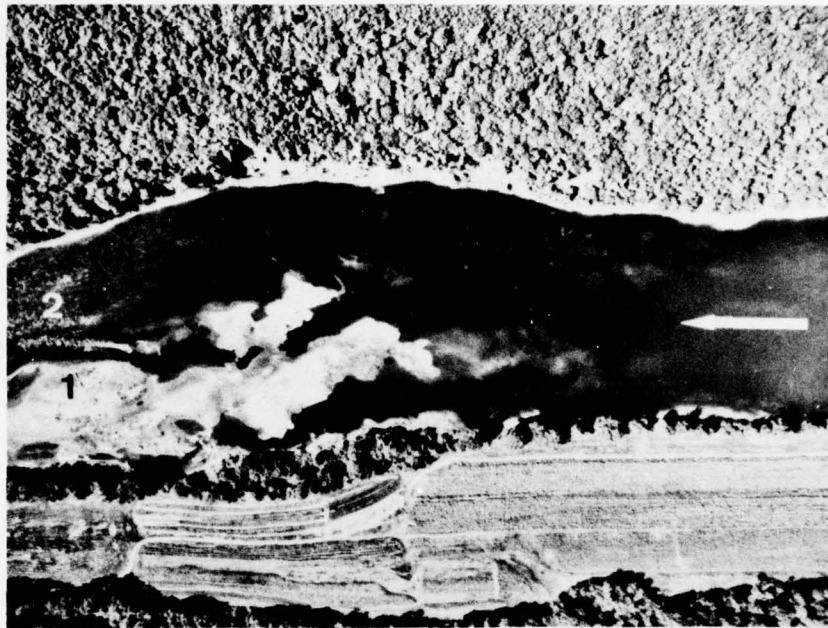
GROUND SURVEYS

During October 1974, cross sections were surveyed in the study reach. The sections were located after examination of black and white aerial photographs. Two additional cross sections were added when the actual surveying was being conducted. The survey was initiated at the crest of Sumner



a. Sumner Falls. 1) Ledge outcrops, vertical drop roughly 15 ft through the falls.
2) Alluvial fan.

Figure 4. Aerial photographs of study area.



b. Slow-velocity reach just above Section 18. 1) River has widened with a deposition zone; exposed bed material and debris can be seen. 2) Ripple section begins at the end of this long pool.



c. Another slow-velocity section near Station 6, opposite Windsor. 1) Main channel meander. 2) Deposition zones with the bottom detail easily shown as light gray.

Figure 4 (cont'd). Aerial photographs of study area.



d. River bend at Section 12. Note the surface constriction as flow reaches the bend. 1) A small surface slick of some type with deterioration caused by the turbulence. 2) Accretion of material on the inside bank.



e. 1) Blow-me-down Brook enters from the New Hampshire side. 2) Main channel nearly in the center of the river. 3) Large rock outcrops visible at low flow (Sections 7-8).

Figure 4 (cont'd).



f. 1) Chase Island below the railroad bridge, Section 2.



g. 1) Boston and Maine Railroad Bridge near the Windsor Treatment Plant. 2) The two mill brooks entering from both sides. 3) Effluent is seen discharging from the plant to the river and remaining alongshore but gradually dispersing. 4) The riprap protecting the pier cribs and deposition zones behind the piers is also visible.

Figure 4 (cont'd). Aerial photographs of study area.

Falls with an assumed starting elevation of 400.00 ft. To convert these elevations to the U.S. Geological Survey (USGS) bench marks, 60.6 ft has to be subtracted. Temporary bench marks were established along the river beginning at Station 12. These spot elevations were located one to two sections apart, and were established to allow elevation readings to be taken on any potential ice jam within the study reach.

The actual surveying of the cross sections was performed by using two methods: wading with a surveying rod, and sounding from a small boat. The sounding method involved two techniques, depending on water velocity and depth. The boat was positioned by being headed upstream into the current. The sounding line (marked at 1-ft increments) with a 2-lb weight at the end was thrown slightly upstream into the current, and the depth to the bottom was recorded when the weight contacted the riverbed. When the velocity was greater than 3 ft/sec and/or the depth greater than 10 ft, a heavier sounding weight (~ 15 lb) was used. The horizontal position in the cross section was measured using stadia from the surveying rod. The accuracy at 300 ft was approximately ± 6 ft because of bobbing of the boat. Proper alignment of the boat in the cross section was maintained through the use of the transit set up on the bank at one end of the cross section. The distance between cross sections was taken from the uncontrolled mosaic of the black and white aerial photographs. Plots of the cross sections are shown in the Appendix.

A continuous water-level recorder was installed on State of New Hampshire property in Cornish, approximately one-half mile upstream from the Windsor Covered Bridge, near the boat landing access. It was installed during January (with assistance of personnel from the USGS in Concord, New Hampshire, and the Reservoir Control Center, New England Division, Corps of Engineers) to record the changes in water level during the formation stage of the anticipated ice jam. However, no ice jam occurred during the ice season, and only peak levels due to snowmelt were recorded.

HYDRAULIC ANALYSIS

The basic hydraulic analysis was limited to the determination of the water surface profiles as calculated using the Computer Program HEC-2, developed at the Hydrologic Engineering Center, Corps of Engineers, Davis, California. This method of calculation uses Bernoulli's equation for the total energy at each section and Manning's formula for determining the head loss between sections. Expansion and contraction coefficients were assumed to be on the order of 0.3 and 0.1, respectively. The energy losses due to the bridge piers were ignored because the necessary field data for using the special bridge routine were not taken and their effects were assumed to be minimal.

The premise for using this program was to establish the usefulness of the data generated for analyzing potential ice jam locations in a river system. Also, this program is available at most Corps of Engineers' division and district offices. A contract with the Dufresne-Henry Engineering Corporation in North Springfield, Vermont, provided computer support in running the HEC-2 program on an IBM-370 system. Data on the following river characteristics were obtained for input to the program: 1) channel cross sections, 2) Manning's roughness coefficient (n) for the channel, and 3) starting elevations corresponding to three specific discharge values (i.e., a rating curve for the downstream section of the river).

The data for the channel cross sections were taken from the field survey, and the distances between sections were scaled from the photomosaic. Manning's n was estimated by taking field observations of the river bottom and bank characteristics, and comparing them with photographs of similar channels with previously determined values of Manning's n (Chow 1959). It is recognized that many factors, such as bed material, vegetation, channel alignment, discharge, etc., influence Manning's n . Values of n for the flood plain were not considered because the flows analyzed for this study were contained within the banks.

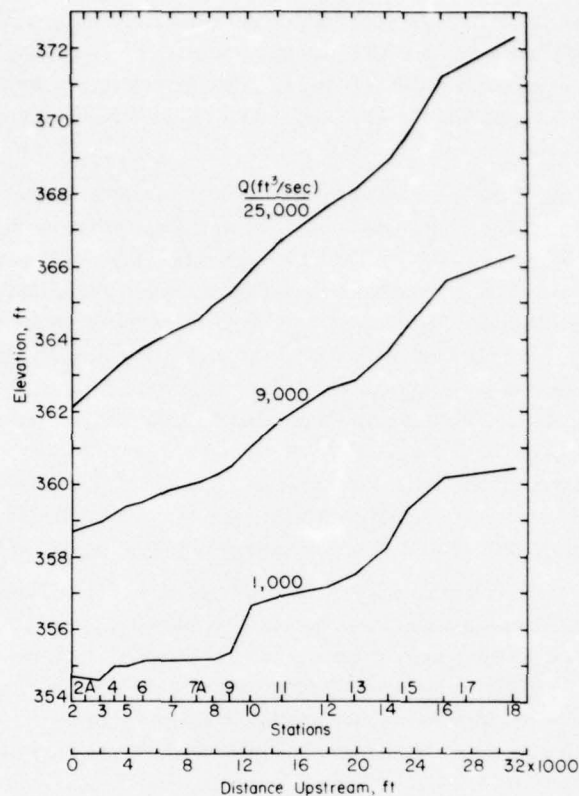


Figure 5. Water surface profiles.

The most difficult data to obtain were the starting elevations to be used at the downstream section (Section 2) corresponding to specific discharges. The nearest continuous river gaging station was located about 10 miles upstream. The Mascoma and the Ottauquechee Rivers flow into the Connecticut River below that gaging station, but above the study reach. Two river flows of 1,000 and 9,000 ft^3/sec were gaged at the downstream section and at selected points upstream. Three additional flows 5,000, 17,000 and 25,000 ft^3/sec were to be analyzed using the HEC-2 program, but there was no stage-discharge curve available for the downstream section. The approximate elevations for these flows at Section 2 were estimated based on the stage discharge data from the White River Junction station and the two measured flows at Section 2, with adjustments in stage height made for the flows from the Mascoma and Ottauquechee Rivers.

A convergence test for the water surface profile was performed for a flow of 9,000 ft^3/sec . Cross section 2 was selected as representative, and a distance of 20,000 ft downstream was used as the length of the channel. The values of the parameters were: $n = 0.03$; bed slope = 0.0028 ft/ft; and starting elevation = 353.1. The computed water surface elevation at Section 2 was 357.97. The measured starting elevation was 357.7 for 9,000 ft^3/sec ; since this difference between the calculated and measured starting elevations is within acceptable tolerances, the calculations proceeded using 357.7.

A trial run was performed using Manning's n of 0.040 for a discharge of 1,000 ft^3/sec and comparing the water-surface profile using an n value of 0.030. The computed water levels at Section 12 were 357.2 and 357.5 for n values of 0.030 and 0.040, respectively. This small difference was not considered significant for the present project; therefore, all subsequent profiles were calculated using $n = 0.030$.

To assess possible errors in the predicted water surface profiles, the starting water surface elevations for each discharge were run with a 1.0-ft increment in elevation difference. The difference in elevation at Section 12 between the two computed profiles for all discharges was less than 0.15 ft.

For the low flow of 1,000 ft³/sec, critical depths were calculated at Sections 3, 13 and 15. Figure 5 shows the water surface profiles for 3 discharges with the starting elevation of 358.7 for the flow of 9,000 ft³/sec. Flows exceeding 25,000 ft³/sec were not considered because the initiation stage of ice jams is thought to occur at low to moderate flows. Detailed water surface profiles for these discharges are on file at USA CRREL as Internal Report 423 (Calkins 1975b).

ANALYSIS OF ICE JAM LOCATIONS

The river sites where ice jams occur have generally been identified through historical records. Attempts to analyze systematically the hydraulic conditions and ice characteristics that initiate the ice jams have been minimal. Several studies have concentrated on the equilibrium thickness of an ice jam once it has formed; Uzunur and Kennedy (1974) have summarized the various methods.

Nuttall (1973) presented some basic work on identifying ice jam sites based on surface ice discharge and a type of Froude criterion. Calkins (1975a) took the same data used by Nuttall and evaluated the critical Froude number based on block thickness and flow depth. This identification scheme for the location of jam sites was based on fragmented ice flowing downstream in a river system.

Continuity of surface ice discharge is assumed with no storage of ice floes between sections. The ratio χ_c of ice surface flux (ft²/sec) between any downstream section and the upstream control section (chosen for this study as Section 18) is

$$\chi_c = \frac{V_i B_i C_i}{V_u B_u C_u} \quad (1)$$

where V = surface velocity (ft/sec)

B = channel width (ft)

C = surface concentration of floating ice (0-1.0)

and the subscripts i and u represent any downstream section and Section 18, respectively.

If one assumes the flow discharge is constant between reaches, $Q_i = Q_u$, eq 1 can be rearranged to yield

$$\chi_c = \frac{A_u B_i C_i}{A_i B_u C_u} \quad (2)$$

where A is the channel cross-sectional area at the respective sections. Equation 2 could have been written in terms of the hydraulic radius R_h , as the term A/B closely approximates A/P where P is the wetted perimeter for open-water conditions.

Frankenstein and Assur (1972) hypothesized that clogging of ice floes would begin when the ice concentration reached 0.707, which probably is a reasonable estimate. A jammed section might be classified as an advanced stage of clogging, reaching a value of $C = 1.0$.

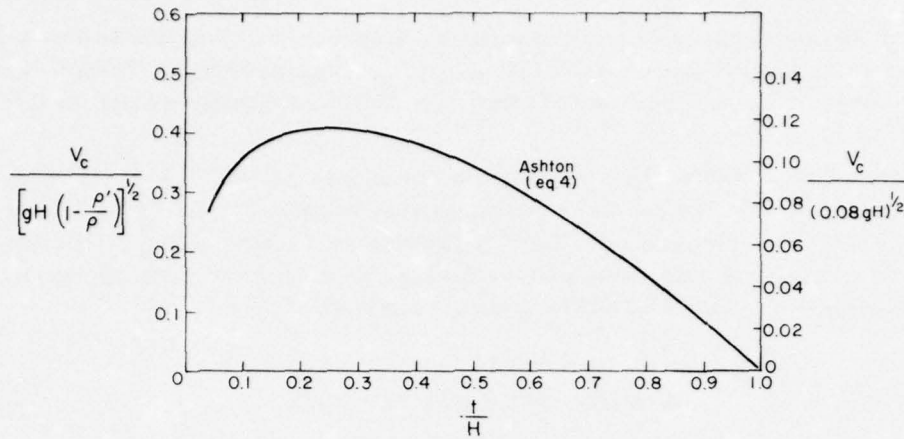


Figure 6. Critical Froude number based on flow depth (Ashton 1974a).

The leading (upstream) edge stability of individual floating ice blocks was analyzed by a number of authors, including, most recently Ashton (1974a, 1974b) and Uzuner and Kennedy (1972). Ashton's work is used here where the critical Froude number is calculated based on a combination of moment equilibrium and hydrodynamic analyses to determine the values of hydraulic parameters for entrainment of the ice floes. The relation between t/H (ice thickness to flow depth ratio) and F_{cr} (critical Froude number) is given in Figure 6, from which is derived the relationship

$$F_{cr} = \frac{V_c}{[gH(1-\rho'/\rho)]^{1/2}} = \frac{2(1-t/H)(t/H)^{1/2}}{[5-3(1-t/H)^2]^{1/2}} \quad (3)$$

where V_c = critical velocity for entrainment of an ice block at the leading edge of an accumulation

g = gravity

t = ice floe thickness

H = depth of flow at the upstream edge of the cover

$\rho'/\rho = 0.92$ for solid ice floes, neglecting porosity effects.

The flow Froude number F_0 for any section can be computed if the depth H and flow velocity V are known

$$F_0 \equiv \frac{V}{\sqrt{gH}} \quad (4)$$

The critical values of the Froude number F_{cr} can be calculated using various ice block thicknesses, since the backwater analysis yields the mean velocity and flow depth as well as other hydraulic parameters. It was assumed for this analysis that the mean channel velocity is equal to the surface velocity although it is recognized that the surface velocity might be in error by 5%, but the assumption is within reasonable limits.

The Froude number criterion described above evaluates the stability of individual ice floes encountering the upstream edge of the ice cover. If $F_0 < F_{cr}$, then the individual ice floes are stable and will not overturn and the ice cover will lengthen upstream by floe juxtaposition until the condition $F_0 \geq F_{cr}$. When $F_0 \geq F_{cr}$ the ice floes will be unstable; overturning and stacking of the floes will occur with potential transport and accumulation beneath the ice cover. The transport

distance depends on local velocity conditions, block size, channel characteristics and other hydraulic conditions (Ashton 1975).

The ice surface discharge parameter χ_c indicates the potential reaches in a channel where the congestion of ice floes is occurring. When the ice concentration equals or exceeds 1.0, it may be assumed that individual ice pieces have to accumulate by thickening or shoving, indicating a potential ice jam location.

The data used in the following figures were generated by the Computer Program HEC-2 except where assumptions were made concerning ice thickness. Figure 7 depicts the channel width B , flow Froude number F_0 and the ice surface discharge parameter χ_c for flows of 1,000, 5,000, 9,000, and 25,000 ft³/sec. For the low flow of 1,000 ft³/sec, critical depth occurs at three sections, as indicated by $F_0 = 1.0$. The surface ice discharge parameter χ_c is better portrayed in Figure 8 for flows of 1,000, 9,000 and 25,000 ft³/sec.

At low flows, χ_c is highly variable, indicating channel constrictions such as: Sections 2A and 4, which are just upstream from the bridge piers; Section 7A, where the channel narrows and deepens just downstream from the ledge outcrops; and Section 12, which is at a sharp bend in the river. These features are easily seen from the aerial photographs (Fig. 4d-e). As the flows increase, the parameter χ_c fluctuates less and approaches the value of 1.0. This is to be expected, since as the river stage rises within the main channel, local sandbars, minor obstructions, and other bottom features are less dominant, and in this reach the stream top width fluctuates little.

To calculate the downstream ice concentration, the incoming ice concentration at Section 18 (upstream control section) is assumed, and then multiplied by χ_c to compute the percentage of coverage by ice. For example, if the ice concentration at Section 18 for a flow of 1,000 ft³/sec is $C_u = 0.60$, then the expected concentration C_i at Section 12 would be 1.21, where $\chi_c = 2.02$. This indicates clogging of ice floes at Section 12 and suggests the possibility of a jam forming in this location. Other potential sites are indicated in Figure 10 by the peak values χ_c . Thus, for a flow of 25,000 ft³/sec at Section 12 ($C_u = 0.60$, $\chi_c = 1.25$), $C_i = 0.75$, and jamming of ice at this section is not a problem because of the increased available surface area for ice floe transport.

Figure 9 presents a frequency distribution of potential occurrences along the entire river where the value of C_i has exceeded 1.0 for three upstream ice surface concentrations and three selected flow rates. Note that the frequency of ice floe clogging occurrences decreases as the flow rate increases. This implies that ice jams from fragmented floes are initiated at low discharges, not as a result of high discharges.

At sections where $C_i > 1.0$, the critical Froude number F_{cr} is next examined to evaluate block stability at the jammed section. Figures 10a-c depict the variation in flow Froude number and the critical Froude number along the river. For flows of 25,000 and 9,000 ft³/sec, F_0 is greater everywhere than F_{cr} for assumed ice thicknesses of 1, 2, and 3 ft. For the flow of 9,000 ft³/sec, the F_0 approaches F_{cr} at Sections 2A, 4, 7 and 12.

At the low flow of 1,000 ft³/sec, F_0 is less than F_{cr} at several sections; this indicates individual ice block stability (no thickening of accumulated ice) at these sites. Also, certain values of F_{cr} are equal to zero at Sections 3, 6, 11, 13 and 15. This corresponds to grounding of ice floes on the channel bottom. Figure 10a depicts this highly variable flow condition for $Q \approx 1,000$ ft³/sec, as indicated by the Froude number, implying ice block stability, instability, or grounding of the floes.

The potential ice jam locations, as indicated by the parameter χ_c for a discharge of 1,000 ft³/sec, are at Sections 2A, 4, 7A and 12 (see Fig. 8). Without any knowledge of the upstream ice conditions, one could assume that potential ice jam sites are located at the sections where χ_c reaches maximum values. For an ice thickness of 1.0 ft, the flow Froude number F_0 is less than the critical

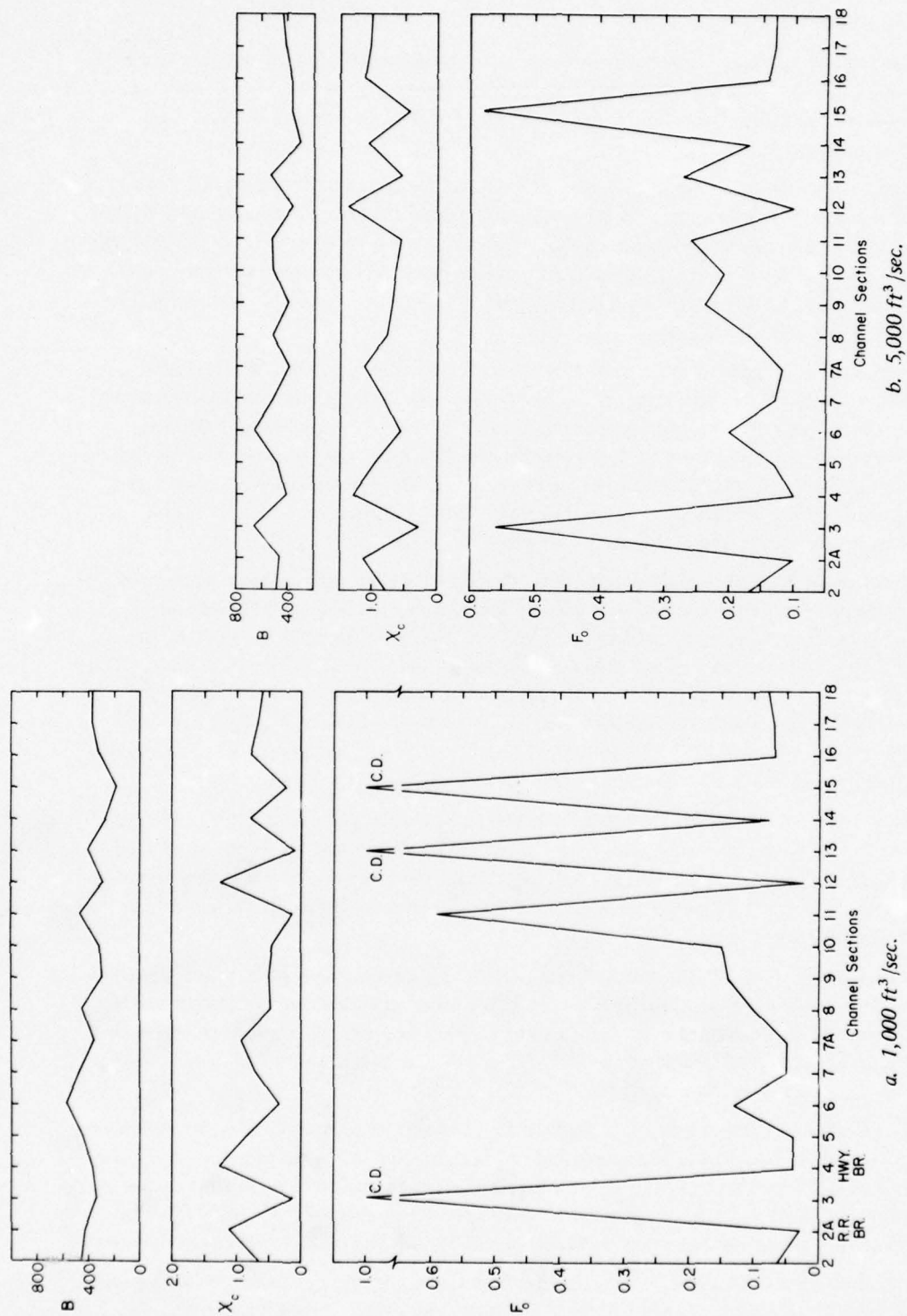


Figure 7. Channel parameters, width B , flow Froude number F_0 , and ice surface discharge X_c . CD = critical depth.

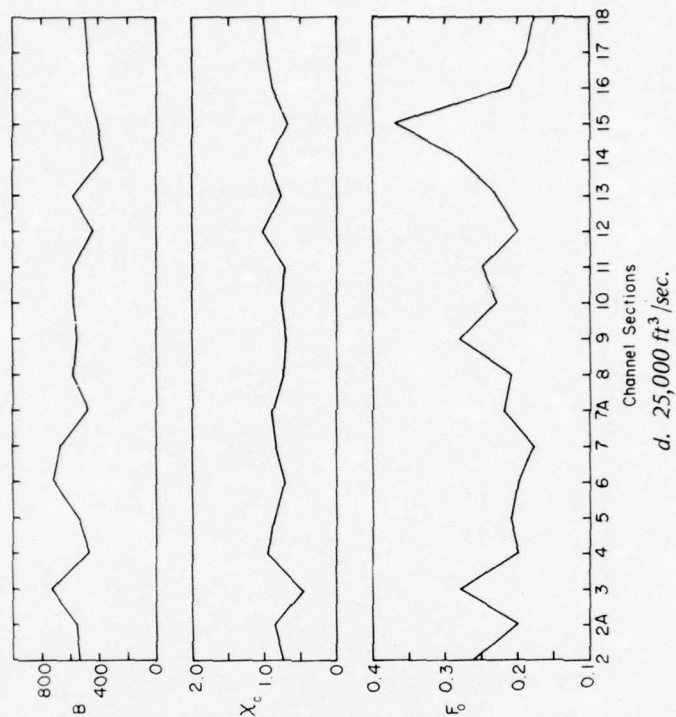
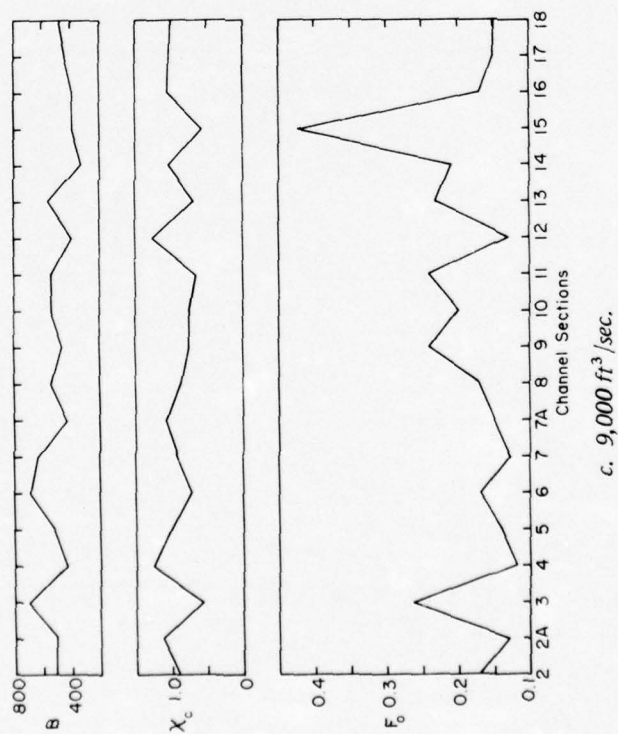


Figure 7 (cont'd).



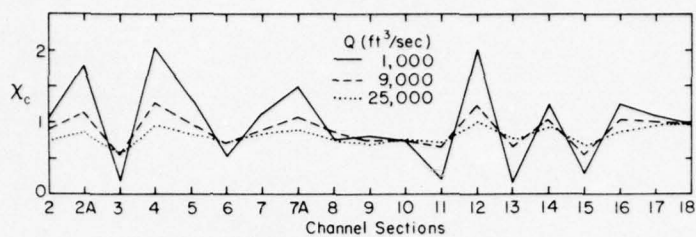


Figure 8. Ice discharge parameter χ_c .

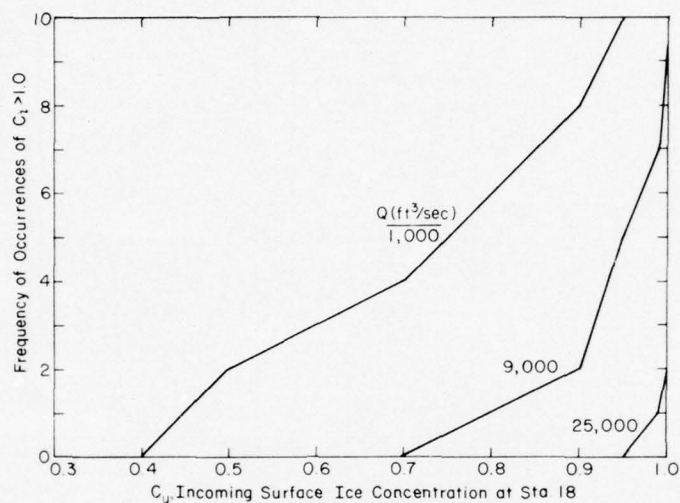
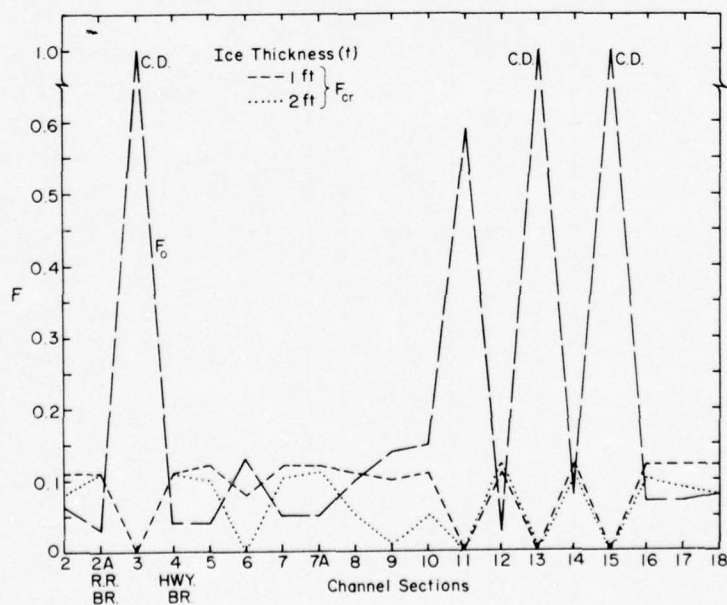
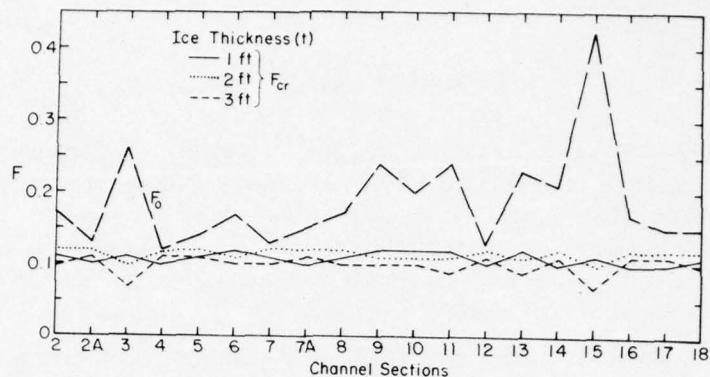


Figure 9. Frequency distribution of potential ice jam occurrence.

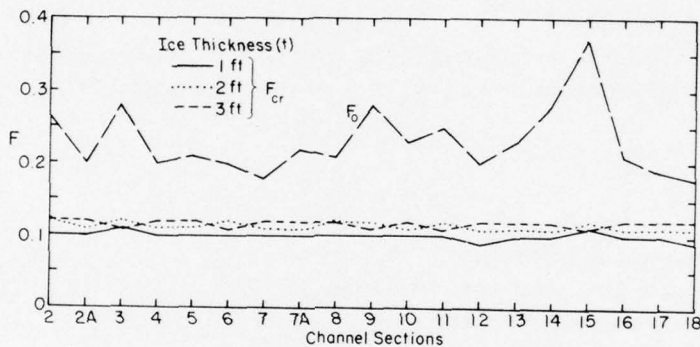


a. $1,000 \text{ ft}^3/\text{sec.}$

Figure 10. Critical and flow Froude numbers along the channel for three ice thicknesses.



b. 9,000 ft³/sec.



c. 25,000 ft³/sec.

Figure 10 (cont'd).

Froude number F_{cr} at all four sections (Fig. 10), indicating no overturning or stacking. If the ice floes are of sufficient internal strength and size, arching of the ice floes could be expected at these four sections. The immediate sections upstream of 2A and 12 have high values of F_0 and low values of χ_c , indicating that clogging is minimal and that overturning of ice floes will take place. Upstream from Sections 4 and 7, the ice will accumulate by juxtaposition until the condition $F_0 > F_{cr}$ is reached. Realizing the high variability of any ice data and the resulting complicated flow patterns at $Q \approx 1,000$ ft³/sec, the F_0 values for the entire reach between Sections 4 and 7A are below or near the critical values, and thus indicate a reach conducive to stabilizing an ice cover of fragmented floes.

When the river flow increases from 1,000 to 9,000, then to 25,000 ft³/sec, the difference between the flow and critical Froude numbers increases, and the individual ice blocks become unstable. The variability in the ice discharge parameter χ_c diminishes as the flow increases, because of the improved surface conveyance of the ice, thus minimizing the potential clogging of ice floes along the river.

Once the ice cover has been formed at low flow conditions between Sections 2A and 10 and during the stage rise every day, the incoming broken ice from upstream will probably be accumulated beneath the cover because the critical Froude number is exceeded when the flow is greater than 5,000 ft³/sec and the release flow from Wilder approaches 10,000 ft³/sec. The constant rising and falling water levels in the reach every day complicate the ice floe behavior.

WINTER FIELD OBSERVATIONS

The formation of an ice cover is complex, with shore ice often the first to appear in the quiescent zones along banks. Frazil ice formation in a river system is associated with turbulent flow and supercooling of the water. The temperature associated with nucleation of frazil ice is only a few hundredths ($\sim 0.05^\circ$) below 32°F . Once the frazil crystals leave the so-called active zone, they tend to concentrate at the water surface, and the development of slush-ice pans or floes from the frazil ice depends in part upon the velocity conditions in the river.

Frazil ice is developed in the White River and moves into the Connecticut River at White River Junction. Frazil is also produced in the Connecticut River, probably below Sumner Falls. Frazil production **does** not usually take place in water velocities less than 2.5-3.0 ft/sec. The average stream velocity in the Connecticut River is greater than 2.5 ft/sec for flows exceeding $5,000 \text{ ft}^3/\text{sec}$.

The quantity of frazil ice production can be large; for example, a basic heat transfer relationship has been formulated to estimate the ice production in a river reach (Michel 1971):

$$Q'_i = \frac{\sum \Psi_i b_i \Delta l_i}{\rho_i g L}$$

where Q'_i = discharge of ice (ft^3/day)

Ψ_i = average heat extracted from stretch i ($\text{Btu}/\text{ft}^2 \text{ day}$)

b_i = width of open water on stretch i (ft)

Δl_i = length of stretch (ft)

L = latent heat of fusion of ice (Btu/lb)

ρ_i = density of ice (slug/ft^3)

g = gravitational constant ($32.2 \text{ ft}/\text{sec}^2$)

If we assume $L = 144$, $\rho_i = 1.78$, $\Delta l_i = 1.0$, $b_i = 1.0$ and $\Psi_i = 1000$ for an air temperature of roughly 20°F , the ice discharge is $Q'_i = 0.257 \text{ ft}^3/\text{day}$ for this one square foot surface area. If the area of open water is $10,000 \text{ ft}^2$, the amount of potential ice discharge is $25,700 \text{ ft}^3/\text{day}$, a staggering quantity.

The combination of frazil ice production and shore ice initiates and completes the cover growth for most river systems in northern areas. Anchor ice was observed on the river bottom between Sections 5 and 7 where low-velocity flows were present. While one of the authors was visiting this site, several passing floes were observed with debris attached to them, indicating that they had surfaced from the bed at an upstream source.

The formation of shore ice and production of frazil began in mid-December 1974 on the Connecticut River and its tributaries. A solid cover did not remain in the study reach until the last week of January 1975, although on several visits to the Windsor area, fragmented floes had arched across the opening between bridge piers, establishing the formation of a temporary solid ice cover extending upstream to Sections 5 and 6. These ice covers were destroyed either by warm weather, or by the increased hydrodynamic forces caused by the rise in river stage because of the release of water for hydroelectric generation. Figure 11 gives an oblique view of the arching of fragmented floes at the bridge piers.

The greatest potential for ice growth occurs over the weekends for the Connecticut River. Normally, no power generation occurs and a minimal flow is maintained. This constant water level allows a uniform ice cover to form, but ice growth depends upon prevailing weather.



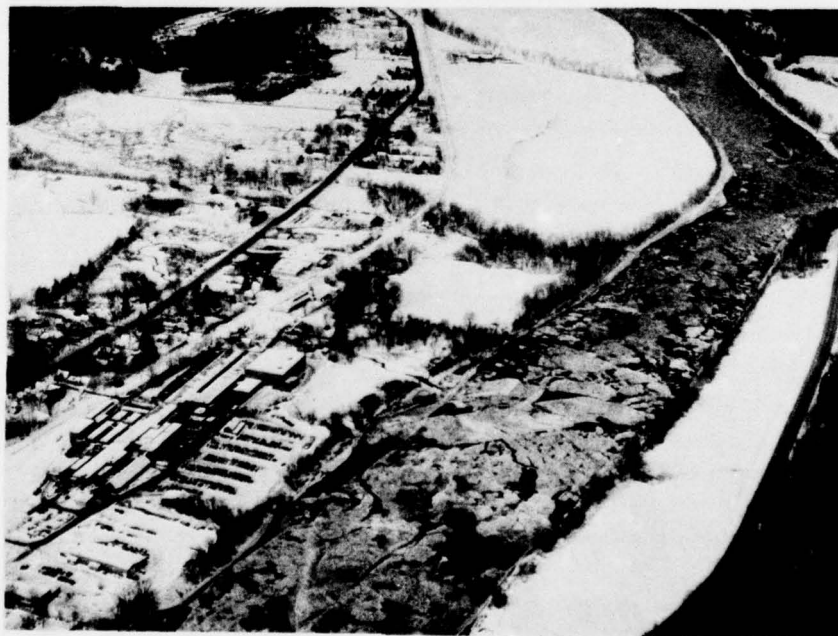
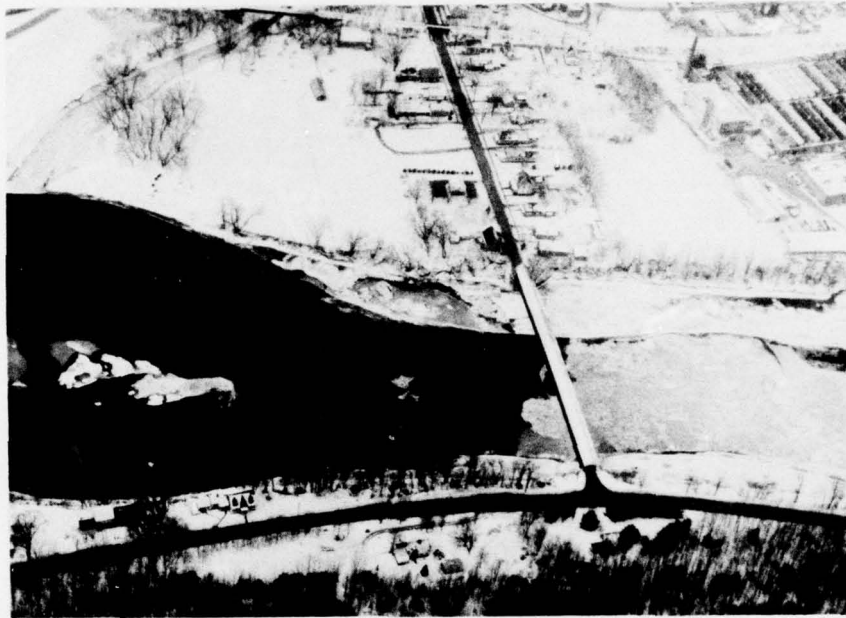
Figure 11. Oblique view of arching of ice upstream of the bridge piers, 24 January 1975.

When power generation begins on Monday, the river rises and the cover breaks up into a wide range of floe sizes. These floes are then transported downstream where arching is initiated at the bridge piers and constricted areas. The ice cover for the 1974-75 season was observed to form at the bridge piers and propagate upstream to a maximum point near Station 18. The thickness of the ice was not measured, as it was not a uniform cover of single thickness, but was composed of frozen multiple thick floes of various dimensions and in various orientations.

The first surveillance flight was flown on 24 January 1975. A solid cover had begun at the two bridges in Windsor and was continuous upstream to about Station 5. Upstream from Station 6, a fragmented cover was forming from floes that had been broken as a result of the power generation that morning. The floes decreased in size as they traveled downstream. Figure 12 shows four sequential oblique views, beginning at the covered bridge in Windsor and continuing upstream to about Section 7. The width of the river in these views is roughly 500-600 ft. Frazil development was also seen in the reaches below Sumner Falls.

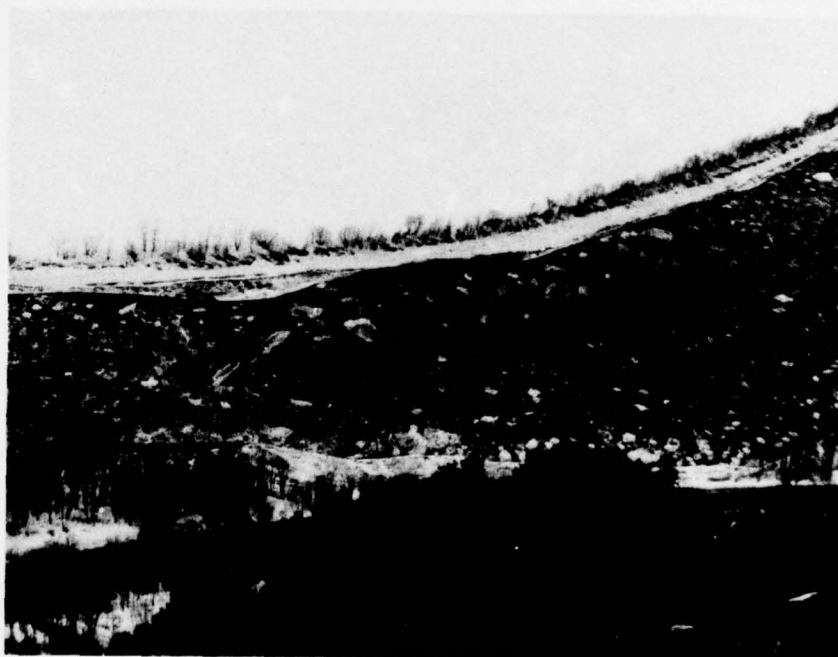
The second and third reconnaissance flights were flown on 7 and 28 February 1975, respectively. On 7 February solid ice extended to Section 13 with a fragmented cover to Section 18. The third photographic flight was completed only two days prior to the complete breakup of the Connecticut River in the Windsor area. Significant melt holes were developing in the high velocity regions of the channel, and cracking and fractured ice was also visible.

Figures 13 and 14 give oblique views of the Windsor area on 7 and 28 February 1975, respectively. Effluent from the sewage treatment plant, as well as a thermal effluent, can be easily seen just above the covered bridge. Figure 15 gives a view near Section 7; the melt hole to the right is the result of both inflow from Hubbard Brook and a high velocity flow region in the cross section. Another melt region can also be seen downstream along the bank of the Vermont (right) side, resulting from spring runoff in the Runnemede Brook.



a. Two views of fragmented ice upstream of the piers at the covered bridge.

Figure 12. Four oblique views, beginning at covered bridge in Windsor, and continuing to about Section 7, 24 January 1975.



b. Upstream views of fragmented ice between Sections 6 and 7.

Figure 12 (cont'd).

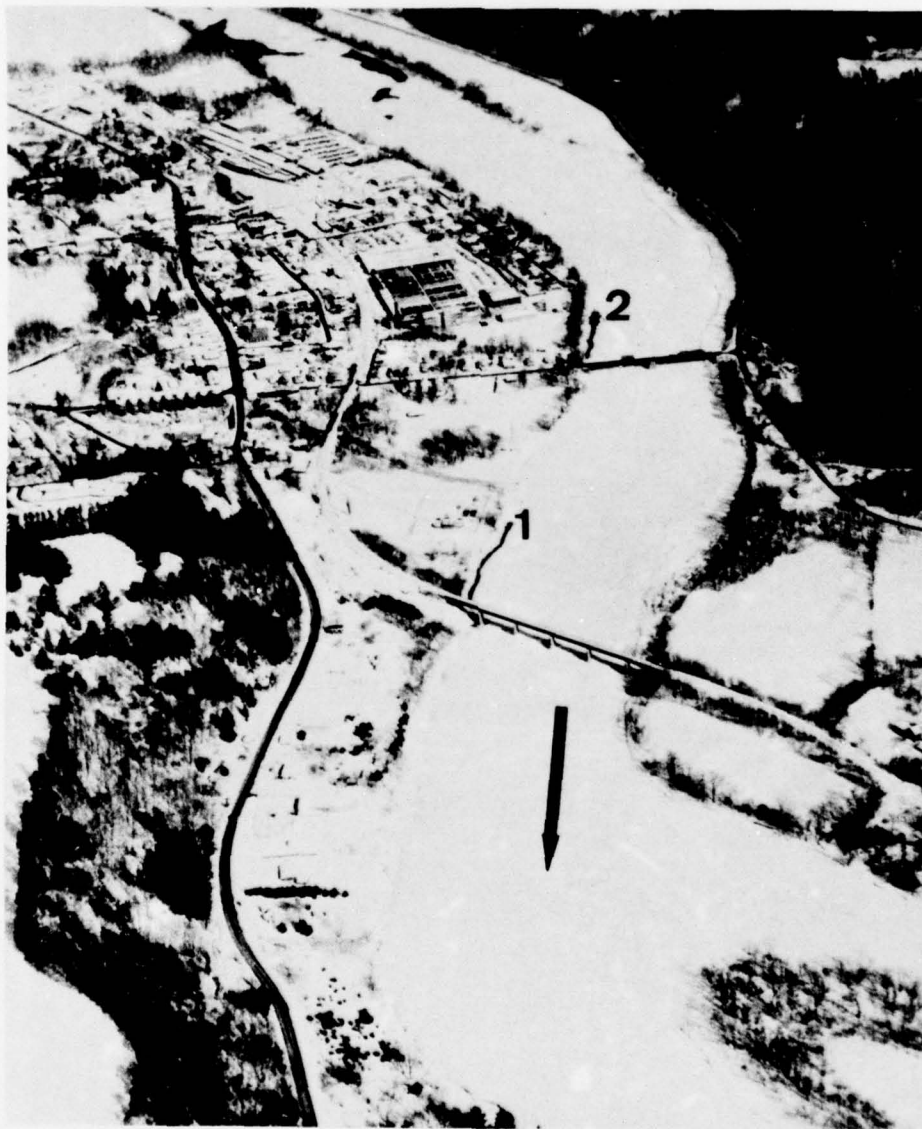


Figure 13. Oblique view of Windsor, 7 February 1975. 1) Effluent from sewage treatment plant.
2) Thermal effluent.



Figure 14. Oblique view of Windsor, 28 February 1975. 1) Effluent from sewage treatment plant.
2) Thermal effluent. 3) Water level recorder site.



Figure 15. View of melt holes two days prior to breakup, 28 February 1975.

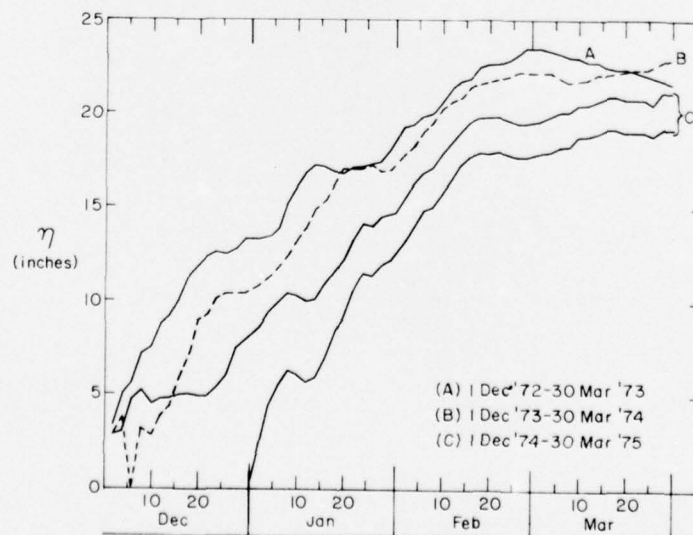


Figure 16. Potential ice growth thickness in the Connecticut River.

Ice thickness profiles [based on an often-used empirical relationship referred to in a monograph by Michel (1971)] were calculated using the number of degree days of frost. The formula is

$$\eta = \alpha(S)^{1/2}$$

where η = ice (in.)

α = coefficient derived from past experience (0.7)

S = degree days of frost ($^{\circ}$ F-days).

Figure 16 presents the potential static ice growth for the last three years based on mean daily air temperature at Hanover, New Hampshire, assuming the ice growth began on 1 December. During the winters of 1972-1973 and 1973-1974, ice jams occurred in the study reach between Sections 4 and 7. It was suspected that the winter was much milder during the 1974-1975 season, but the potential ice thickness growth appeared not to be significantly below that of the other two years on 1 March. The weekend air temperatures for these three years were also investigated, and it appears that the complete freezeup of the river might have occurred before mid-January during 1972-1973 and 1973-1974, but no records were available. The ice growth was also calculated, using 1 January 1975 as the date of first ice cover for the 1974-1975 season, and the results showed that it was below normal (see Fig. 16), but again a direct comparison cannot be made with the other two years.

Figure 17a shows the shearing and failure planes near the shoreline. The piling of fragmented ice (Fig. 17b) results from the daily fluctuation of the river stage (3-5 ft). This continual process of shearing and piling is one of the major contributors to the formation of ice jams in this reach of the river. As a result of the overnight freezing, breaking of the ice cover, and transport downstream, a greater volume of ice was produced and accumulated in the channel than would result from a uniform cover, if it could be formed.

The sites of previous ice jams in the Windsor area have ranged between the railroad bridge and Section 7. The shallow depths, increased river width, and sandbars from Section 5 to Section 7A indicate areas of low velocity. The shallow depth allows potential grounding of ice floes and resulting piling. The effect of the backwater from the downstream Brattleboro hydroelectric dam on the flow conditions in this area has not been established. The influence of the solid ice cover in the backwater could prohibit transport of ice from the Windsor reach.

Figure 18 gives two views of the study reach taken in 1973. The remains of the ice collar after the ice had receded about 8 ft are still evident on the middle bridge pier. The massive piling of ice floes indicates the potential thickness of the jams and the resulting water levels that can be expected with flows well below ice-free flood discharges.

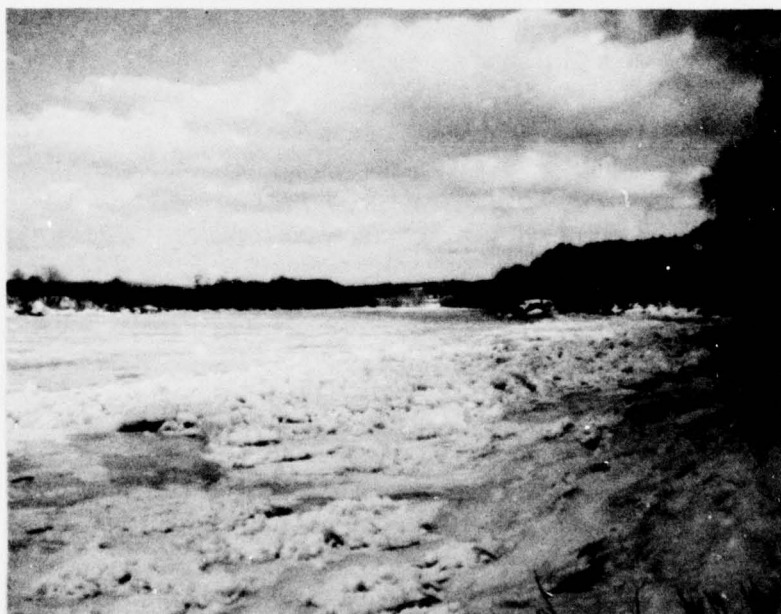
CONCLUSIONS

The reasons that a jam did not occur in the Windsor area during the 1974-1975 winter are probably many: a solid ice cover did not form until late in January; the cover thickness appeared to be less than usual; a mild breakup period occurred with no rain, leaving a majority of the ice to melt in place; and the White River contributed little ice.

A hydraulic analysis of the flow conditions through the reach yielded certain criteria for identifying ice jam sites. When the surface conveyance of ice is significantly reduced, the individual ice floes tend to clog and potential jamming exists at these sites. The results presented in Figure 11 reveal that the surface conveyance of ice improves with increased discharge, and that ice jams



a.



b.

Figure 17. Shearing and failure planes near the shoreline (a) and piling of ice floes (b).

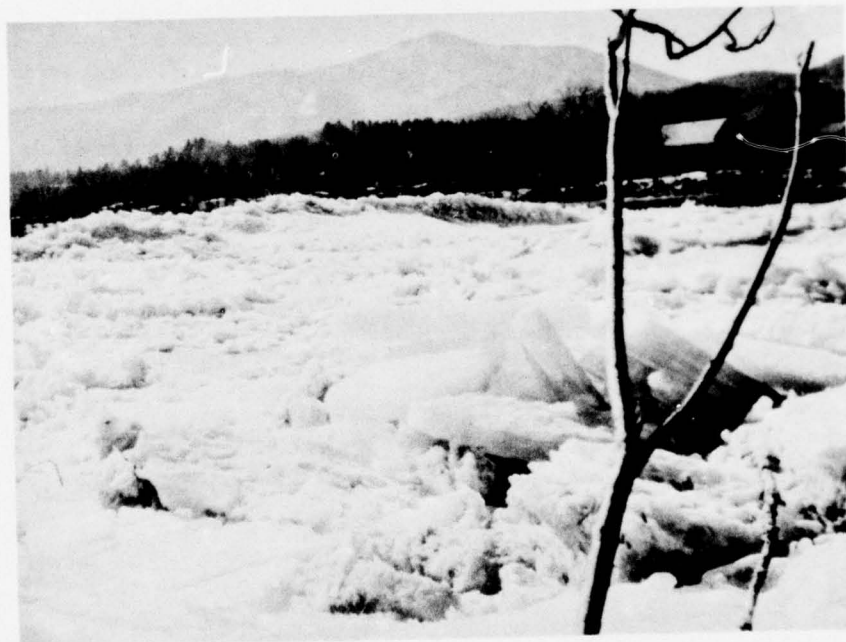
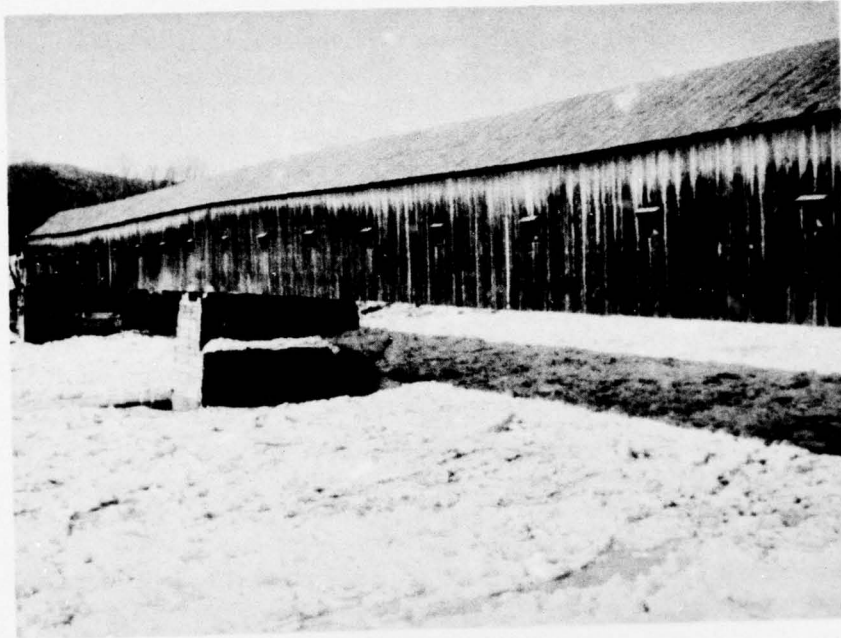


Figure 18. Views of the 1973 ice jam in the Windsor area.

resulting from clogging of individual floes have a greater potential at low flows than at high flows. This simple ice discharge routing scheme is based on continuity of ice transport between sections. No account has been made for the storage of floes, progression upstream of a cover if a jam is encountered, or thickness of an ice jam once formed. However, Uzuner and Kennedy (1974) developed a model for ice jam evolution to calculate the ice jam thickness and water level from river and ice characteristics. Application of their model should be considered in future studies.

The Froude number analysis at each section allows the determination of whether individual ice blocks (of a given thickness) will be stable or will overturn. If the individual floes are hydrodynamically stable and have sufficient dimension and internal strength, arching of floes can be expected, and the cover can progress upstream. If the blocks are unstable, they will overturn and be transported beneath the cover, with arching possible but dependent upon the Froude number. The downstream distance and necessary hydraulic conditions for block transport under the ice cover have yet to be identified, but model studies are presently underway on these topics.

Ice jams on the Connecticut River in the Windsor area probably form as a result of many adverse conditions, such as: full-depth constrictions which decrease the surface conveyance of ice transport and enhance the ice-arching conditions (bridge piers); potential blockage of ice transport near Section 2 due to a solid cover at the upstream end of the backwater from the hydroelectric dam at Brattleboro, Vermont; deep pools just upstream of the bridge piers; and shallow depths near Sections 5 and 6, permitting the grounding of ice at low flows and the increase of fragmented ice floes to the area because of the power generation schedule at Wilder Dam.

The ice discharge parameter χ_c indicates peak values at the two bridges at low flows ($Q < 5000 \text{ ft}^3/\text{sec}$). The flow Froude numbers are less than critical Froude numbers at these sections and in the immediate reaches upstream of the two bridges (Sections 4-7a), enhancing the arching capabilities of the fragmented ice. Grounding of ice floes is indicated by the critical Froude number being equal to zero at Section 6.

The role of aerial photography in ice jam conditions cannot be overstressed. Pre-jam photography helped in identifying the channel obstructions, aided in surveying the cross sections, and provided general information on the channel characteristics. The winter photography helped to identify the formation stage of ice cover growth and to document the breakup of the ice.

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APPENDIX: LOCATIONS AND PLOTS OF
CROSS SECTIONS FROM SUMNER FALLS
TO CHASE ISLAND, CONNECTICUT RIVER

